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Distributed multi-generation: A comprehensive view

Gianfranco Chicco *, Pierluigi Mancarella

Dipartimento di Ingegneria Elettrica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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Abstract

The recent development of efficient thermal prime movers for distributed generation is changing the focus of the production of electricity from large centralized power plants to local generation units scattered over the territory. The scientific community is addressing the analysis and planning of distributed energy resources with widespread approaches, taking into account technical, environmental, economic and social issues. The coupling of cogeneration systems to absorption/electric chillers or heat pumps, as well as the interactions with renewable sources, allow for setting up multi-generation systems for combined local production of different energy vectors such as electricity, heat (at different enthalpy levels), cooling power, hydrogen, various chemical substances, and so forth. Adoption of composite multi-generation systems may lead to significant benefits in terms of higher energy efficiency, reduced CO_2 emissions, and enhanced economy. In this light, a key direction for improving the characteristics of the local energy production concerns the integration of the concepts of distributed energy resources and combined production of different energy vectors into a comprehensive distributed multi-generation (DMG) framework that entails various approaches to energy planning currently available in the literature. This paper outlines the main aspects of the DMG framework, illustrating its characteristics and summarizing the relevant DMG structures. The presentation is backed by an extended review of the most recent journal publications and reports.

Keywords: Cogeneration; Distributed energy resources; Distributed multi-generation; Optimization; Polygeneration; Trigeneration

Contents

Abbreviations: CCHP, combined cooling heat and power; CHCP, combined heat cooling and power; CHP, combined heat and power; DCN, district cooling network; DER, distributed energy resources; DG, distributed generation; DH, district heating; DMG, distributed multi-generation; DR, demand response; DS, distributed storage; EDS, electricity distribution system; FC, fuel cell; GDS, gas distribution system; HDS, hydrogen distribution system; ICE, internal combustion engine; ICT, information and communication technologies; LCA, life cycle assessment; MT, microturbine; PV, photovoltaic; PV/T, photovoltaic/thermal.

* Corresponding author. Tel.: +39 011 090 7141; fax: +39 011 090 7199.
E-mail addresses: gianfranco.chicco@polito.it (G. Chicco), pierluigi.mancarella@polito.it (P. Mancarella).

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1. Introduction

The new millennium has started with several innovations driven by fast evolution of the technologies in the energy sector. A strong impulse towards the diffusion of new energy systems has been given by the development of economical energy-efficient technologies, regulatory incentives related to energy production from renewable sources and to promotion of more sustainable environmental-friendly (low-emission) generation solutions, the evolution of the electricity markets, more and more binding local emission constraints, and the need for improving the security of supply to reduce the energy system vulnerability. Undoubtedly, the needs for coping with the climate change threat and for keeping the commitments taken up by several countries by signing the Kyoto's Protocol represent further key drivers towards pushing the changes the energy sector is undergoing.

The scientific community is addressing these issues with widespread approaches, taking into account technical, environmental, economic and social issues. Concerning the local electricity production, in particular, significant advances are in progress according to the distributed energy resources (DER) paradigm [1], with various *decentralized* aspects that from the energy production standpoint are focused on the concept of distributed generation (DG) [2–4]. The ongoing changes are significantly impacting on the role and operation of the electrical system infrastructure. In this respect, a number of innovative DG technologies have already reached the commercial stage, providing solutions available to the consumers. In particular, among the various generation solutions at a *small scale* (below 1 MW_e), the commercial success of the internal combustion engine (ICE) and more recently of the Microturbine (MT) [3–7] is greatly due to the significant energy efficiency improvement obtained from *cogeneration* of heat and electricity to satisfy the demand of the corresponding energy vectors. In addition, fuel cells (FCs) are seen as promising alternatives in the next future, owing above all to their potentially extremely high electrical efficiency, also in combination with turbine technologies for setting up hybrid cycles [4–8]. Combined heat and power (CHP) plants are widely acknowledged for their high potential in terms of energy saving with respect to the separate production [9,10]. However, only the commercialization of economically effective *local* generation technologies such as MTs, ICEs and FCs has enabled cogeneration to be profitably set up on a scale much smaller than classical district heating (DH) or industrial applications. In this respect, nowadays a DER system based on small-scale cogeneration technologies can result more convenient than an electricity-only DG system.

Contemporarily to the diffusion of decentralized electricity generation sources, new technologies for the generation of cooling power are being developed around the world, and the performance of traditional ones is being improved. This is primarily due to the uprising demand of seasonal air conditioning that has boosted the enlargement of the market for cooling equipment [11]. In addition, in some countries the energy prices (of electricity, oil and natural gas, *in primis*) have skyrocketed because of different reasons, including inefficient operation of the energy markets, as well as political interactions with the countries holding the bulk of fossil fuel resources. Furthermore, cooling loads are mostly needed when electricity rates are higher, that is, in electrical peak hours. In this respect, high cooling loads have contributed to electrical load peaking and subsequent network congestion and failure events in different power systems worldwide [12,13]. This has strengthened the awareness of governments, manufacturers and communities about energy and environmental issues, pushing forward the search for more efficient and economic equipment for local energy generation.

The various technologies currently available for cooling (as well as heat) generation can be heat-fired or electricity-fired, so allowing for various combined schemes with CHP systems. Combination of cogeneration technologies to various *thermally fed* systems such as absorption or engine-driven chillers [14–17] allow for setting up a so-called *trigeneration* system. In addition, high-efficiency *electro-energetic* technologies such as electric heat pumps [14,16] well fit into the existing energy systems to enhance the overall performance. This kind of combined systems can exhibit excellent energy, environmental and economic performance. Indeed, feeding different technologies with different fuels for producing different energy vectors gives birth to a variety of alternatives for more effective design and planning of the energy systems. In addition, the possibility of co-generating hydrogen and of using it as a storage energy vector, in case exploiting volatile electricity production from renewable sources such as wind or sun, represents a further variable that could be advantageously exploited. Hence, the possible benefits from the combined production of multiple energy vectors (e.g., electricity, heat, cooling, hydrogen, or other chemical products) paves the way to future scenarios focused on the development of *multi-generation* (or poly-generation) solutions.

All the above aspects lead to substantial changes in the global vision of the energy sector, calling for structuring a comprehensive framework of analysis. In particular, the scientific literature is relatively recently addressing the local production of energy by using different approaches and viewpoints. Several specific frameworks have been formulated within the scientific communities dealing with energy resources, power systems, environmental impact, economic and financial analysis, and so forth. However, nowadays the interconnections among the energy-related issues are so tight that an interdisciplinary view for bridging the gap among the various standpoints is indispensable.

A survey of the relevant publications on scientific journals in the last years (2001–2007) shows that the largest part of these publications is still related to cogeneration. However, the number of research papers related to multi-generation concepts and applications is lately exploding. Very recent reviews have been focused on comprehensive energy modelling [18], large-scale approaches and methods to decentralized energy planning [19], technologies for combined cooling, heat and power production [20], and structured frameworks for addressing the evolution of the electrical systems in terms of diffusion of DER [1,21–23].

This paper presents a comprehensive view of the application of various small-scale *local* multi-generation solutions. The presentation of the relevant concepts is accompanied by a review of the state of the art of the scientific literature in various areas. The emergent issues on decentralized energy generation are illustrated under a unified approach that, stepping beyond the already innovative DG approach [4], can be called the *distributed multi-generation* (DMG) paradigm. A number of significant recent developments for small-scale applications is addressed, summarizing their characteristics and their role within the DMG framework. Furthermore, details are provided on the characterization and interaction of the most widespread multi-generation system components. The list of references has mainly been selected from the most recent journal papers and high-profile research reports relevant to multi-generation issues.

2. The background frameworks

2.1. Decentralized electricity generation: background concepts on distributed energy resources

The DER paradigm represents the current view of concepts like "*dispersed generation and storage*" and "*demand side management*". In fact, the acronym DER encompasses three main aspects, whose focus is set on the electrical standpoint:

- distributed generation (DG): local energy production from various types of sources [2,3,24–26];
- demand response (DR): energy saving brought by the customer participation to specific programmes for reducing the peak power or the energy consumption [27–30];
- distributed storage (DS): local energy storage with different types of devices [31–34].

The bases of the DER theoretical framework were set up more than two decades ago [35,36], but at that time the evolution of the technologies was not yet ready for implementation of the proposed solutions on a broad basis. Various applications have been developed during the years mainly in the industrial sector (*i.e.*, for self-production and energy backup during emergencies). In recent years, there has been a significant diffusion of DG in several countries, while the implementation of DR and DS solutions is rapidly gaining interest [37]. Nowadays, the present technologies and economic systems are enabling the diffusion of DER applications within different energy contexts, up to the individual *non-industrial* users [1,22]. More specifically, the *key issues* related to the diffusion of DER solutions can be summarized as follows:

- DG has emerged as a key option for promoting energy efficiency and use of renewable sources in alternative to the traditional generation [38];
- the adoption of DER solutions can *defer* huge investments in new large generation plants, substations or infrastructures, whose long return time of investment does not fit with the current trend towards setting up rapidly profitable and market-orientated solutions [39,40];
- a multiplicity of local generation sources may lead to preferring the type of energy with higher local availability of the corresponding "fuel", thus impacting on the development of the fuel supply infrastructures [41];
- the trend towards distributed micro-power could be significant in terms of increasing the local energy source availability, reducing both the energy dependency [42] and the vulnerability of the electrical system from the effects of grid congestions, reducing service interruptions, blackouts, vandalism or external attacks [42,43] through the formation of self-healing energy areas [44,45];
- the development of competitive electricity markets has increased the customer participation to the market, providing solutions to exploit the price elasticity to the electrical demand [27,40,46];
- the local resources connected to the electrical grid may provide benefits on the electrical network reliability (e.g., by reducing the total energy not supplied after a service interruption) and power quality (by including power conditioning options based on updated power electronics [23,47] within the grid interface systems) [48,49];
- the evolution of DER technologies is leading to revisiting the standards dedicated to their interconnection to the electrical distribution systems, with definition of updated requirements concerning the protection systems [50];
- the presence of local electricity generation sources brings into play the *local* emission problem, above all in densely populated *urban areas* with plenty of potential receptors [51], not addressed with large and "far" electricity generation plants [52–54].

2.2. Multi-generation background concepts: cogeneration

Cogeneration solutions can exhibit excellent overall energy efficiency and allow for significant primary energy saving with

respect to the separate production of heat and electricity [9,10]. As a consequence of the primary energy saving, CHP systems can also be an effective means to pursue the objectives of the Kyoto's Protocol in terms of greenhouse gas emission reduction [55,56]. However, on a country-wise basis these benefits are strongly related to the generation mix characteristics of the relevant power system [55]. Hence, adoption of cogeneration has been pushed forward from a regulatory point of view in several countries [57–59], above all in those ones where the power generation mix is mostly based on thermal plants, so that CHP production can also bring consistent CO_2 emission reduction. Besides the incentives available for cogeneration, assimilated to renewable sources owing to its intrinsically enhanced energy efficiency and CO_2 emission characteristics, CHP system profitability could be further improved by the possibility of accessing new *energy-related markets* (e.g., for white certificates, green certificates, or emission allowances) [60–67]. In addition, the possible lower overall hazardous pollutant emission [56] could further push towards adoption of CHP systems in the presence of stringent policies regarding emission constraints in terms of NO_x, SO_x, and so forth.

Profitable deployment of CHP solutions is strongly dependent upon the presence of simultaneous demand of the relevant energy vectors in a broad time span over the year. In the past, this condition was mostly satisfied by industrial and DH installations, considering that reasons of technological scale allowed only relatively bigger plants to be cost-effective [5,9]. Today, availability of DG technologies with good electrical and excellent overall efficiency has enabled cogeneration to be adopted also on a small-scale [7] and even micro-scale [54] basis, with suitable applications ranging from residential houses to schools, restaurants, hotels, and so forth [5,7,68].

On the basis of all these factors, CHP systems are likely to play an important role in setting new perspectives for modern and future energy system assets.

2.3. From cogeneration to trigeneration

The presence of a threefold energy demand (namely, of electricity, heat and cooling) leads to the possibility of profitably setting up *trigeneration* plants [4,5,68–74], also identified as combined heat, cooling and power (CHCP) or combined cooling, heat and power (CCHP) plants. The trigeneration concept represents an extension of CHP, that is, the production *in situ* of a threefold energy vector requested by the user from a unique source of fuel (e.g., natural gas).

Classical trigeneration plant solutions are represented by coupling a CHP prime mover to an absorption chiller fired by cogenerated heat [75–77]. In this scheme, the produced thermal power is exploited also in the summertime to produce cooling. In this way, one of the biggest shortcomings that often make cogeneration unprofitable, that is, the lack of adequate thermal request throughout the whole year, is made up for by *transforming* the cooling demand into thermal demand. As a consequence, the prime mover can run for longer time at averagely higher load, thus allowing for better energy and environmental performance, optimized regulation strategies and design, and shorter investment pay-back times [4,68,70,76,78]. Of course, adequate cooling demand in the summertime and thermal demand in the wintertime are needed to make trigeneration solutions economically feasible. In this respect, potential applications on a small-scale basis include hospitals, hotels, food industry, schools, department stores, commercial buildings, offices, residential districts, and so forth [20,68,76,79–81], besides other applications at larger scale such as airports [82,83].

2.4. Towards multi-generation

From a *generalized* point of view to trigeneration planning [84–87], it is possible to look at the plant as a *black-box* (see also Section 3.2) with an array of inputs and a manifold output. Hence, the trigeneration planning problem can be extended to encompass the analysis of different equipment for electrical, thermal and cooling generation, besides the classical schemes with absorption chillers fed by cogenerated heat [20,73,84–89]. In particular, different solutions can be envisaged for the local production of cooling power. Among these, it is possible to mention electrical chillers, direct-fired absorption chillers, and engine-driven chillers. All these solutions may have a *heat recovery* option, so leading to potentially set up a cooling-and-heat cogeneration system to be coupled to a "classical" electricity-and-heat cogeneration systems.

The analysis of different trigeneration alternatives (components and schemes) may become particularly interesting when cooling generation is needed not only for air conditioning, or in any case not only for the summertime span (*seasonal* trigeneration). In this respect, it must be pointed out that most of equipment for cooling generation are reversible, so that they could actually operate under both *cooling mode* and *heating mode*. This simplifies the plant schemes and improves the plant economy, owing to the possibility of saving the purchase of some equipment and of better exploiting the CHP production [85,90,91]. In fact, the variety of technologies that can be adopted in the trigeneration plants allow for optimally managing the different energy vectors inside the plant in order to endeavour the most viable and effective solutions (also on the operational level) for different types of applications and from different standpoints (energy saving, emission reduction, minimum costs, and so forth).

Considering the combination of CHP systems with different technologies for thermal/cooling generation, the enthalpy levels at which thermal/cooling power can be produced can be manifold. For instance, heat generation equipment such as electric heat pumps could be used to produce hot air for space heating, while a cogenerator such as an ICE could produce hot water for domestic use and steam for feeding an absorption chiller. Hence, from the point of view of considering the physical carriers that are generated for carrying different forms of energies, it is possible to identify cases of tri-generation, quad-generation, and so forth, depending on the number of outputs. In this respect, the trigeneration concept can be further generalized by introducing the rationale of *multi-generation* [92,93], as referred to the production of electricity, cooling

power and heat, with the two latter ones in case available at different enthalpy (temperature/pressure) levels. Furthermore, the concept of multi-generation can encompass the provision of additional outputs such as hydrogen, dehumidification, or other chemical substances used in specific processes [94–97].

The overall picture is that the energy system designer has now a wide range of alternatives to combine together to set up a local energy system for manifold energy production. Effective combination, at the planning and at the operational stage, of these different alternatives can bring enhanced benefits in terms of energy efficiency, emission reduction, economic profitability, and reliability and quality of the service provided to the user [16,85–87,90–92,98,99].

3. The distributed multi-generation (DMG) approach

3.1. A novel decentralized energy generation paradigm

Availability of thermal-based local power plants, whose thermodynamic and technical characteristics allow for multi-generation applications, may change dramatically the economics and the convenience of the local generation itself, even for market-niche technologies [100]. In particular, the combined occurrence of various benefits from DER *and* multi-generation makes the bridge between the decentralized electricity generation and solutions for production of other energy vectors. This paves the way to the effective deployment of local multi-generation systems, stepping beyond the DG rationale, already defined as ‘‘the paradigm of the new millennium’’ [4], towards the even more innovative DMG approach.

In the light of the above premises, the applications developed in the decentralized energy production area can be categorized, in structural and functional terms and in the increasing order of complexity, as

(a) *classical cogeneration* (single input fuel, double output, single site);
(b) *multi-generation* (single/multiple input fuel, manifold output energy vectors, single site);
(c) *distributed multi-generation* (single/multiple input fuel, manifold output energy vectors, multiple sites).

The distinction among single site and multiple sites refers to the physical location of the energy systems with respect to the *energy infrastructures* [101]. In particular, single site solutions are most focused on the conversions among various types of energy to satisfy the local demand (typical of industrial plants). Instead, the case of multiple sites takes also into account the local delivery of the related energy vectors through suitable infrastructures [41]. In this respect, the electrical grid or electricity distribution system (EDS), the gas distribution system (GDS), a DH network and a district cooling network (DCN) are infrastructures already encountered today. In addition, solutions with multiple fuel may include the supply of the thermal equipment with bio-fuels [102] or bio-masses [103,104], as well as hybrid solutions coupling the local generation equipment to solar or wind energy systems [105–107]. A Hydrogen distribution system (HDS) could also be envisaged in the next years within a hydrogen economy scenario, for carrying in the energy vector to supply the plant (input) or to deliver it out to further systems after local generation and in case storage in the plant (output) [108,109]. On the above considerations, apparently DMG solutions could show the highest potential within *urban areas*, where interconnected infrastructures and variety of energy demand are mostly available.

3.2. Structures, components and energy flows in DMG systems

A multi-generation plant can be *conceptually* seen as composed of the combination of local subsystems producing electricity, heat, cooling, hydrogen and so on. Fig. 1 shows the basic layout with the relevant energy flows (normally not simultaneously present). In addition, although not shown in the figure, other products/effects such as various chemical compounds or dehumidification can represent relevant multi-generation outputs.

The core of the system is represented by two main *physical* blocks:

- The CHP block, containing a cogeneration prime mover and, usually, a combustion heat generator, for thermal back-up and/or peak shaving. It produces electricity W and heat Q to various possible final uses, including the production of cooling power or additional thermal power after feeding the additional generation plant (AGP).
- The AGP block, that can be composed of different equipment for cooling and/or heat production, as well as hydrogen and other products, and can be schematically represented in a

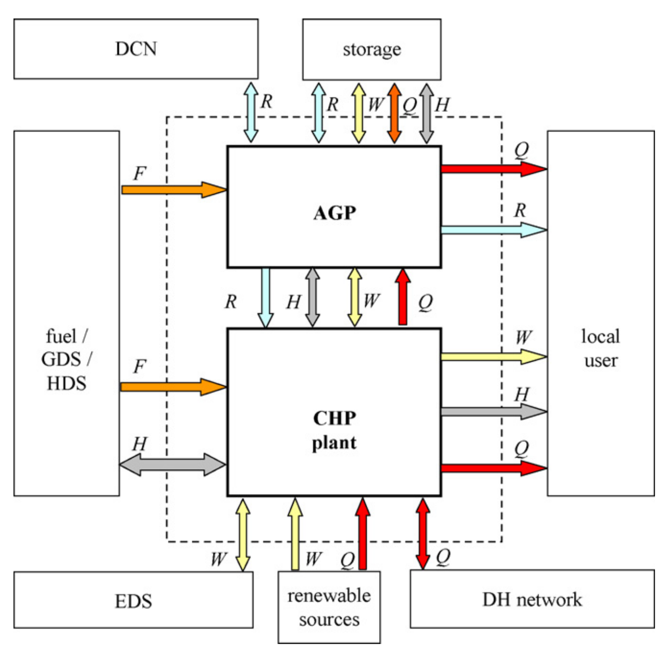

Fig. 1. *Black-box* layout and energy flows in a multi-generation plant.

general way according to two *linking modes* with respect to the CHP side [84,87]:

- *separate* (or *parallel*) generation mode: the AGP is "decoupled" from the cogeneration side, *i.e.*, it is fed by energy vectors (typically natural gas) not produced by the CHP plant;
- *bottoming* (or *series*) generation mode: the AGP is cascaded to the *topping* cogeneration plant, in general distinguishing the "*electrical bottoming cycle*" (where the energy vector feeding the AGP is electricity) from the "*thermal bottoming cycle*" (where the energy vector feeding the AGP is heat).

Each component of the multi-generation system can be characterized by means of its *black-box* characteristics [84], that is, its energy input–output interactions with the other plant components, typically described through conventional energy efficiencies [9,16], and without going into further details with the equipment internal description. In turn, combination of various equipment into aggregated block-components can be described by composite black-boxes, up to model the whole multi-generation plant as a black-box, with the aim of limiting the number of variables into play. This is consistent with the need for endeavouring solutions leading to efficient use of energy, in terms of minimizing the input energy for obtaining a given energy output for the specific application [110].

3.2.1. Energy flows in DMG systems

For a more specific description of the energy flows reported in Fig. 1:

- The entry F represents in general thermal power contained in the fuel (e.g., based on the fuel lower heating value [5,6]). Direct fuel-firing is the typical input to the cogeneration side, with diesel, natural gas, dual-fuel [4,5], and bio-masses [111] (in case co-fired with natural gas [103,104]) as typical fuels for small-scale applications based on MTs or ICEs. Similarly, hydrogen could be used for supplying a FC, with in case an intermediate stage for instance with natural gas as direct input to be used for further hydrogen production [97,108,109]. In addition, also the AGP could be fed with different fuels (*separate generation*). Again, the most typical fuel input to the AGP is natural gas. Different fuel typologies could be used for different equipment (e.g., hydrogen for FCs, fuel oil for the heat generators, natural gas for separate cooling generation in the AGP); in this case, the different input thermal energy typologies should be assessed on the basis of the relevant fuel lower heating value. Fuel distribution networks could be available at the DMG plant inlet. In particular, the GDS is already widely spread in urban areas, while the HDS is under analysis in different countries (see for instance [112]) and could be envisioned for future applications [108,109,113].
- Electrical energy W can be produced by the cogeneration plant, bought in from the EDS, or generated by external renewable sources such as PV or wind-based systems. The electricity can be used to supply the user's needs, as well as to feed the AGP in order to produce thermal/cooling energy or hydrogen from electrolysis (*electrical bottoming generation*). Electricity might be as well sold out to the EDS.
- Thermal energy Q (at different enthalpy levels, typically in the form of hot water and/or steam) is typically produced by the CHP side to supply the user. In addition, it can also be used to feed the AGP in order to produce additional heat for the user (e.g., hot air by means of heat pumps) or cooling power through absorption chillers (*thermal bottoming generation*). In case, thermal power can also be exchanged with DH networks, or be recovered from the chillers to supply part of the thermal load. Renewable heat could also be generated by means of solar thermal systems.
- Cooling energy R (typically in the form of chilled water) is produced within the AGP to supply the user's requests. In addition, exchanges with a DCN are in theory possible. Finally, part or all of the cooling power can be fed back into the CHP plant, for instance to pre-cool the intake air of a turbine or MT in order to improve the electricity generation capacity and efficiency of the overall system [72,114,115].
- Hydrogen energy H could come from a possible HDS to supply a FC in the CHP plant, could be produced within the generation block from methane steam reforming or from electrolysis typically starting from renewable sources [97,108,109], could be injected into the HDS for further distribution, could be stored within hydrogen storage units for successive utilization [116,117], and finally could be exploited by the local user (e.g., for transportation or industrial applications [118–120]).

3.2.2. The cogeneration core

The core of a multi-generation plant is the CHP side, composed of the cogeneration prime mover, whose capacity is in case dwindled over more units, plus a combustion heat generator composed of boilers. If the multi-generation plant is not meant for stand-alone operation [121], connection to the EDS is usually available, that guarantees higher reliability and flexibility to the plant. Likewise, the possibility of exploiting a DH network as a sink for exceeding or lacking thermal production opens to further operational options for profitably managing the plant.

On a small-scale basis, the cogeneration technology nowadays mostly adopted is the ICE [3–5] that can be considered as a consolidated benchmark. Future development might include the co-utilization of natural gas and hydrogen with higher performance and lower emissions [122]. However, the MT, the breakthrough technology of the last decade, is rapidly increasing its market shares [4,5]. More specifically, the growing success of MTs is due to their excellent modularity and flexibility characteristics (above all if used in clusters [123]) that make them suitable for a wide range of applications and loads, as well as fuels [4]. In addition, in terms of NO_x and CO pollutant emissions, the full-load performance of natural gas-fuelled MTs is very good with respect to the natural gas-fuelled ICE [5,6], so that MTs can be more and more encountered where there are specific binding environmental constraints (for instance, urban areas [7,124,125]).

Cogenerative FCs are still too expensive for a broad market exploitation, but a number of examples available in the literature hint that they might play an important role in the next future as a high-efficiency low-emission local energy generation source for various capacities and applications [93,105,113,126–129]. In particular, the possibility of adopting FCs in combination with MTs or gas turbines could lead to promising perspectives for setting up CHP hybrid schemes with excellent energy and environmental performance [8,98,130–132]. Hydrogen is typically locally generated from natural gas through steam methane reforming [109,118], with potential for co-production of electricity, heat and useful chemicals such as nitrogen by means of an internal reforming fuel cell [97]. In case, the steam needed for the reforming process can be supplied by the cogenerator itself (the fuel cell in case coupled to a turbine in a hybrid cycle), so leading to a high-efficiency multi-generation scheme [8,130,133,134].

3.2.3. The additional generation plant

The AGP equipment can be fed by different energy vectors, also according to the *separate* or *bottoming* generation modes outlined above.

More specifically, if the AGP is *separate* from the cogeneration side, typically the following technologies of chiller/heaters directly fed by fuel can be adopted:

- Gas-fired absorption chillers [14–16]: these so-called *direct-fired* chillers are fed by gas, whose thermal content is transformed into cooling effect directly in the machine by exploiting the absorption process. The chiller is most of times double-effect [14–16,135], while the higher-performance triple-effect technology [16,20,135] is being lately introduced in the market. The heat, usually discarded by means of a cooling tower, could be in case recovered (for instance, by means of an electric heat pump to increase the heat temperature to levels suitable for user's applications [8,136]). Often, the machine is reversible and could be used also under heating mode as a heat pump to save the purchase of additional boilers.
- Gas-fired absorption heat pumps [16,17,137]: these machines are born for drawing thermal power from a ''free'' heat source (typically the atmosphere or ground water) and for supplying it to a hotter ambient after increasing its temperature. Basically, from the outside they can be seen as boilers (they are also directly-fed by fuel) but with efficiency possibly higher than unity. However, the output heat temperature is often limited to less than 70–80 °C.
- Engine-driven chillers [15,16,73,89]: in this case, a conventional vapour-compression chiller, instead of being driven by an electrical compressor, is driven by a mechanical compressor, whose shaft is directly connected to a conventional internal combustion engine. Seen from the outside as a black box, the system, also directly fed by fuel, is completely equivalent to a gas-fired absorption chiller, although energetically an engine-driven chiller has the advantage that a part of the fuel input can be more easily recovered, as in normal cogeneration ICEs [15,16,20]. Thus, the machine can provide at the same time heat and cooling power.
- Engine-driven heat pumps: the engine-driven chiller is often a reversible machine able to work as a heat pump; in this case, the possibility of recovering thermal power also from the driving ICE allows for enhanced performance as a total energy thermal generator [16,89,138,139].

For a *bottoming* AGP for heat/cooling production, it is possible to consider:

- Indirect-fired absorption chillers [14–16,73]: in the classical trigeneration case, differently from a direct-fired chiller, the absorption machine is supplied by heat produced in cogeneration (''*thermal bottoming*''). The equipment can be both single-effect (usually fired by hot water) or double-effect (usually fired by super-heated water or steam) [14–16]. The triple-effect chillers now appearing on the market typically require higher pressures and temperatures than double-effect ones, which could limit their applications in bottoming schemes and make them more suitable to be direct-fired [20]. Again, the thermal power discharged to a cooling tower could be in theory recovered [8,136]. As for a gas-fired absorption chiller and in analogy with a gas-fired heat pump, also in this case the machine is often reversible and could be used for heating purposes as an absorption heat pump, in case co-fired by natural gas [17,88,137].
- Electric chillers [14–16] and electrical heat pumps [9,14–16]: the electric chiller is the classical solution to produce cooling power, and in a multi-generation system the feeding electricity could be produced in the CHP unit (''*electrical bottoming*''). In most cases, however, an electrical heat pump is adopted, since it is a reversible machine capable to work in both heating mode and cooling mode (as a chiller, then). In this way, the CHP installed electrical capacity and the working hours of the plant throughout the year are optimized, exactly as for the thermal power with an absorption chiller fed by cogenerated heat. When adopting an electrical chiller, the discharged thermal power could be sometimes recovered by means of a heat recovery condenser [140].

The above equipment represents the most widespread technologies for DMG systems. However, other technologies, typically heat-fed and thus combinable to CHP systems, can be encountered in the AGP, above all for building applications. In particular, *adsorption* [16,141–143] and solid or liquid *desiccant* [16,144,145] systems are more and more often adopted for multi-generation of electricity, heating, cooling and dehumidification [94,146,147]. Often, combination with low-temperature thermal sources such as solar power results attractive [148–151].

In addition, the various AGP schemes can be completed by thermal/cooling storage systems [16,75,140,152–155], in order to improve the plant design, management and economics by enabling the creation of a thermal/cooling energy buffer to be profitably used for thermal load shifting and control purposes.

3.2.4. The role of renewable sources, hybrid energy systems and distributed storage alternatives

The term ‘‘cogeneration’’ is traditionally adopted with reference to the combined production of heat and electricity from fossil fuels. However, other types of cogeneration sources can be adopted, *in primis* from *solar power*, that allow for clean high-performance solutions [156]. In this respect, increasing interest is being lately gained by applications of solar technologies for multi-generation. More specifically, photovoltaic (PV) modules, thermal collectors, and hybrid photovoltaic/thermal (PV/T) systems can be effectively coupled to bottoming cooling/heating equipment. In particular, although in theory electricity can be produced in a PV system and then utilized to feed an electric chiller, it results more energetically and economically effective to adopt heat-fired cooling technologies (namely, adsorption, absorption or desiccant systems [148,151]) to be fed by cogenerated heat in a PV/T solar system (solar trigeneration), or by heat produced in a solar collector. In particular, PV/T solar units for cogenerative and trigenerative applications bear the additional intrinsic energy benefit that the optimized cooling of the solar modules brought by the heat recovery system brings along an increase in the PV electrical generation efficiency owing to decrease of the module temperature [157,158]. The rationale of the utilization of solar systems for both heating and cooling generation is the same as for adopting conventional CHP plants in trigeneration applications. In fact, the solar thermal power is optimally exploited throughout the year, namely, in the summertime for cooling generation, and in the wintertime for heat generation (besides electricity, in case) [151,159]. As a further upside from adoption of solar-powered air conditioning, the correlation of the cooling loads with the solar radiation intensity is very high in most applications. Typically solar heat is generated at temperatures relatively low (below 90 °C). However, multi-generation with concentrating PV/T systems, with thermal power produced at temperatures higher than 100 °C and thus viable for a number of applications (including steam production and coupling to double-effect absorption chillers), has also been experimented to be quite effective [160].

Interesting perspectives are emerging from the integration of fossil-fuelled CHP and renewable sources, even though the latter provide fluctuating power supply [161], thus giving birth to a *hybrid* DMG system. Indeed, the flexibility offered by coupling controllable CHP plants of various scales to volatile resources such as wind power could greatly enhance the overall energy and economic performance of the integrated energy system [162,163]. Even higher performance could be reached, also from an environmental point of view, by additionally combining PV systems [164,165]. Further benefits could be brought by adopting reversible electrical heat pumps to exploit the possible unbalanced exceeding electrical production from renewable sources for heat or cooling generation within the composite DMG system [163,166,167]. In any case, when resorting to the use of local production renewable sources, an interesting economic option is offered by the possibility of selling electricity to the grid according to feed-in tariff structures [168], in compliance with specific environmental regulations [169].

Regarding the optimal utilization of uncertain renewable sources for electrical production, high-performance *distributed electrical storage* devices could play an important role [31–34], although normally they are rated on the basis of a limited capacity in order to guarantee service continuity in any condition to particularly sensitive users (e.g., data storage centres or hospitals). Further important perspectives in this direction could be related in the future to applications where *hydrogen* is produced by electrolysis and used as an equivalent electricity DS means [116,170], thus improving the flexibility as well as the economics of the plant. In this light, the integration of small-scale wind or PV system with hydrogen has already shown potential benefits for stand-alone applications [121]. The effective exploitation of such a DS solution in DMG applications has to be thoroughly evaluated, including environmental benefits [171] and possible integration with the electricity market [116,117].

Adequate control strategies for the renewable-based multi-generation system equipped with DS devices should be set up, in order to cope with load transients and keep the generation-load balance [172,173]. In addition, suitable filters [47] might be needed in order to ensure a certain voltage quality level in the presence of highly non-linear electronic converters [23] adopted for connecting the dispersed generation units to the grid.

When dealing with renewable sources, specific analysis models can be needed for thorough energy and environmental assessments. In particular, the bulk of the energy and environmental burden in energy systems run on fossil fuels is related to the plant operation [174,175]. Differently, while operation of renewable-based systems is virtually energy-and-emission-free [176], the major environmental burden is due to plant building and decommissioning. These aspects can be adequately addressed by means of cradle-to-grave life cycle analysis concepts and life cycle assessment (LCA) techniques [105,177–179]. This aspect is also particularly relevant when dealing with different alternatives (renewable or fossil sources) for hydrogen production along with or in alternative to electricity production [171,180,181]. Bio-masses exhibit the peculiar characteristics of absorbing CO_2 during their life, often described in terms of *CO_2-sink* behaviour; then, energy systems based upon bio-masses (see for instance [104]) also should be evaluated by resorting to LCA techniques [111]. On the above premises, a full comparison of DMG systems based upon renewable or fossil sources should exploit LCA-based approaches, taking into proper account the impact of the relevant *external costs* associated to the whole life cycle [51,179,182,183].

Focusing on DMG from renewable sources for building applications (mainly based on solar systems), the energy used in buildings during their operational phase (for heating, cooling, ventilation, electrical uses, etc.) is the largely prevailing part of the energy consumed during their life cycle [184]. As such, the efforts towards promoting small-scale DMG applications are fully justifiable even in the more comprehensive context of LCA. For instance, potential benefits have been shown in [106] concerning the life cycle energy savings obtainable from combining PV and heat recovery for multi-generation applications in buildings.

3.3. Interconnection and coordination of DMG systems

In a DMG system, several local multi-generation units like the one in Fig. 1 can be scattered over the territory and can interact with each other by means of the available energy infrastructures (Section 3.1). The overall design of the local plants can be then coordinated to envision some supervised or consortium-based management of the energy vectors. Even a re-classification of the energy customers according to their manifold energy use [185] could be needed in order to fit the characteristics of the DMG framework.

A typical situation in which DMG plants could be effectively coordinated occur in the presence of a group of multi-generation points belonging to an energy district, managed by a single energy service company and connected only through proprietary networks. In this case, coordinated control and possible optimization of the plant operation according to specified objective functions can be developed within the local system [124]. Alternatively, a group of multi-generation points managed in a coordinated way can be connected through public networks (or networks with different owners) that supply all or part of the energy vectors. In this case, interactions with the use of these energy networks calls for a dedicated economic treatment, for instance by applying energy wheeling charges [186].

From the operational viewpoint, the DMG system could be subject to coordinated control and possible combined optimization of the local plant operation. The role of information and communication technology (ICT) in this case is crucial for reliable interconnection and management of the multi-points through distributed computing techniques such as agent-based applications [48,187–189].

4. Survey of recent publications within the distributed multi-generation framework

On the scientific literature side, the evolution of the recent contributions can be framed within a transition from specific DER and multi-generation applications to the comprehensive DMG concept. This section reviews significant recent contributions dealing with various approaches for the characterization, planning, evaluation and optimization of decentralized energy systems, in order to highlight their distinguishing features and their specific domains of application, all encompassed within the DMG framework.

4.1. Approaches to decentralized and multi-generation planning and analysis

Some emergent concepts referred to multi-generation system issues include virtual power plants [190], micro-grids [191–193], integrated energy systems [146], energy hubs [194,195], multi-source multi-product energy systems [97], and intelligent power grids [196]. The most significant references available to date in the literature are briefly summarized here.

4.1.1. Virtual power plants

The *virtual power plants* framework has been conceptually established in 1997 [197], with the main objectives of enhancing the visibility of the DER, providing suitable interfaces among the local components, activating distributed control strategies, and addressing the optimal use of the available capacity. Specific aspects of the framework include the promotion of the adoption of ICT and the study of the interactions with the energy markets. The characteristics of a virtual power plant are similar to the ones of a plant connected to the electrical transmission system. Hence, it is possible to formulate optimal generation schedules from the management of a portfolio of DER, also taking into account the internal operating cost structure (assumed as private information in the competitive energy markets) and exploiting the possibility of participating to the ancillary service markets for providing regulation and reserve services [1,40,198–200].

4.1.2. Micro-grids

Micro-grids [193] are small local distribution systems containing generation and load, whose operation could be totally separated (*autonomous*) from the main distribution system or connected to it (*non-autonomous*). A micro-grid is operated from a control centre, by monitoring the energy demand/supply and optimizing the use of different distributed generators, customers participating to DR programs and DS. The micro-grid concept focuses on the integration of multiple DER into the electricity grid, with several aspects concerning the grid interface (including the application of evolved power electronics and control system technologies [23]) and reliability [192]. The network interface sees the micro-grid as a single node with possibility of dispatching power in different ways within the local electricity distribution system. In particular, the autonomous micro-grid operation is critical, due to possible problems in voltage and frequency control. Conversely, managing a non-autonomous micro-grid could be helpful in case of fault to the main distribution system, feeding part of its loads during the operations for fault detection and service restoration [201]. The introduction of micro-grids would require revisiting the protection schemes and the standards of conduct of the distribution systems, by introducing smart switches for assisting the disconnection/reconnection of the micro-grid to the main distribution system. The benefits of using micro-grids include high availability of DER, modular operation planning, increase in economic efficiency from combined production of different energy vectors, possible resource optimization and management of the energy mix. In addition, a single energy service company could perform integrated management of the various resources. This would lead to effective synergies for personnel resources, primary energy purchase and plant maintenance, and the creation of a unique energy bill, thus providing significant advantages to district-sized communities [202]. Dedicated strategies can be developed for minimizing the fuel consumption within the equipment operating in the micro-grid [203] or for evaluating the optimal operation in technical and economic terms [204,205].

4.1.3. Integrated energy systems

The *integrated energy systems* framework [146], launched in 2001 by the US Department of Energy and associated to the distributed energy program [206], is focused on the integration of distributed generation equipment with thermally activated technologies. This programme is based on laboratory applications, e.g., with composed systems including MTs with heat recovery, air conditioning and ventilation, desiccant and absorption chiller units. The specific aspects refer to the maximization of the efficiency of the energy use, the reduction of the emissions to the environment, the improvement of power quality and reliability, the study of the characteristics of more flexible solutions for meeting the peak power demand with respect to large centralized power plants. The laboratory activities are sided by the formulation of mathematical models of individual devices and integrated energy systems. A relevant objective is the development of test protocols and perspective standards for the development of integrated energy solutions.

4.1.4. Energy hubs

The *energy hubs* framework [194,195] is being developed within the project "*vision of future energy networks*". The focus is set on the *long-term evolution* of the energy systems (time horizon of 30–50 years). The energy system structures are revisited without considering the limitations provided by the actual constraints. Multiple energy vectors are converted, conditioned and stored in centralized energy hubs. Specific consideration of multiple energy carriers (other than electricity) in the form of energy interconnectors enables integrated transportation of different forms of energy (electrical, chemical, thermal). Supply diversification, for which the supply no longer depends on a single fuel or network, is needed to prevent reliability reductions due to the limited maintenance that may occur in a market-orientated system. In addition, supply diversification provides more degrees of freedom for selecting the supply source and for possible optimization within the energy system, also taking into account availability of storage from various sources (including hydrogen). The phases of the project envisage the development of the modelling and analysis framework, the determination of optimal system structures and operation strategies, the development of tools for comparing the optimal structures and strategies to the conventional ones, and eventually the identification of transition paths from the existing status to the optimal solutions. The system components are characterized as by using input–output models (like the black-box approach mentioned in Section 3.2), describing only the energy-bases relationships through efficiencies and conversion factors. The relationships among the components are modelled through coupling matrices.

The framework based on *multi-source multi-product* energy systems [97] has been introduced following the energy hubs concept. The framework is developed for dealing with multi-generation energy systems with multiple inputs, including also storage. Again, the system components are characterized by using input–output models, with the energy interactions modelled through coupling matrices.

4.1.5. Intelligent power grids

Other comprehensive approaches have been established starting from the electrical side and infrastructures, to incorporate more extended energy-related issues. Besides several projects at the national and trans-national levels, the main approaches are related to investigate the role of future *intelligent power grids* [196]. In particular, two approaches have emerged in the U.S. and in Europe. The corresponding platforms involve representatives from various sectors, including market and transmission and distribution system operators, industry, research bodies and regulators. The *GridWise*$^{\text{TM}}$ [207] approach was set up in 2004, reflects the vision of the U.S. Department of Energy and is aimed at refocusing the research activities concerning the infrastructure of the electrical systems. In particular, the main aspects concern the deployment of ICT to create an open but secure system architecture with suitable communication techniques and related standards, the promotion of enhanced participation of the electricity consumers in the operation of the power grid, and the reinvention of the industry infrastructure to support innovation. The European technology platform *smart grids* [208,209] was set up in 2005 to create a joint vision of European networks for the next decades. The focus is set on several aspects related to the electricity networks, including infrastructure renewal, security of supply, network interoperability, liberalised markets, central generation, DG and renewable energy sources, DR and demand-side management, environmental issues, regulatory and social aspects.

4.2. Multi-generation system optimization

The high complexity of the issues regarding the energy planning and management of multi-generation systems calls for powerful analysis tools [210]. In this respect, several papers have been lately issued on the optimization of multi-generation systems. More specifically, these optimization problems can be schematically grouped according to various time frames the analysis is developed within, identified in the literature as

- *short-term*, considering the operational planning of the system in a given period (e.g., one year);
- *long-term*, consistent with the formulation of the plant design problem over the plant useful life.

Within these time frames, the system operation is typically considered as a succession of steady state conditions, for instance using a discrete step for the time scale not lower than 1 h, in order to neglect the faster effects on the dynamics of the equipment operation. Another typical feature of most optimization methods is that the system model is based on a synthetic black-box approach, in which the relevant variables are energies, conversion factors, equipment efficiencies, and the descriptors of the interconnections among the system units.

Table 1 summarizes the characteristics of the optimization methods for trigeneration and multi-generation systems presented in recent journal publications, indicating the different formulations and solution methods adopted. The variety of

Table 1
Characteristics of recently published optimization methods applied to multi-generation systems

Reference	System	Time scale	Objective	Solution method
[211]	Trigeneration	Short-term	Min{energy cost}	Linear programming
[212]	Trigeneration	Short-term	Min{energy cost}	Genetic algorithms
[97]	Multi-generation	Short-term	Min{energy cost}	Lagrangian multipliers
[213]	Trigeneration	Short-term	Min{annual costs}	Branch and bound
[83]	Multi-generation	Short-term	Min{annual costs}	Linear programming
[214]	Trigeneration	Short-term	Min{exergy costs}	System partitioning
[91]	Trigeneration	Short-term	Max{gross operational margin}	Branch and bound
[215]	Trigeneration	Short-term	Multi-objective: min{annual costs, CO_2 emissions}	Linear programming
[98]	Trigeneration	Short-term	Multi-objective: min{annual costs, CO_2 emissions}	Evolutionary algorithms
[93]	Multi-generation	Short-term	Multi-objective: min{annual costs, CO_2 emissions}	Evolutionary algorithms/ linear programming
[124,125]	Multi-generation	Short-term	Multi-objective: optimal energy pricing (energy system); Min{annual costs} (multi-generation system and consumers)	Pareto optimization (energy system pricing); Linear programming (multi-generation system and consumers)
[91]	Trigeneration	Long-term	Max{net present value}	Branch and bound
[92]	Distributed multi-generation	Long-term	Max{net present value}	Genetic algorithms

these formulations is wide enough to prevent one from setting up a unified framework for carrying out comparisons among the different problem structures.

In the *short-term*, the objective function is typically formulated in economic terms, in some cases taking into account a further term related to CO_2 emissions. Nevertheless, there are different approaches and details concerning the optimization problems.

A first set of papers refers to minimizing the energy costs for purchasing the input energy vectors, for instance electricity (from the grid) and gas (from the GDS). The paper [211] deals with minimization of the energy costs for a trigeneration plant operating with assigned load patterns. No possibility of selling electricity is considered. The operational variables are the fractions defining the partitioning of the gas turbine output and of the gas turbine exhaust heat. There is no coupling among the variables in the time domain. Results of parametric analyses are provided for variable sizes of the equipment. The solution for each size is obtained from a linear programming model. In [212], the minimization of the energy costs is formulated by taking into account the coupling among the time instants given by the equipment start-up and shutdown, associated to additional cost components. The on/off operational schedule of the units is assumed as decision variable, resulting in a mixed 0–1 linear programming model for multi-period operational planning of district heating and cooling plants. Genetic algorithms are used as the solution method, comparing the results with those obtained by using a branch and bound technique. In [97] the optimization of a multi-source multi-product energy system is set up to minimize the total energy cost in the system. The costs are modelled by using quadratic functions of the power consumption of the sources. The optimization problem with convex model is solved by applying the Karush–Kuhn–Tucker first-order optimality condition. This method has the characteristic of providing the marginal costs of the energy carriers at input and output as by-product of the solution.

Another set of papers deal with the minimization of the annual (fixed and variable) costs. The determination of the optimal plant configuration of a commercial building is addressed in [213], for given annual demands of electricity, heat and cooling. Electricity is purchased at fixed contracts and no electricity can be sold to the grid. The resulting mixed integer/linear programming model is solved by using a branch-and-bound technique. The paper [83] deals with the operation and planning optimizations for a multi-generation system in an airport. In the short-term time frame, the objective is the minimization of the annual operation and maintenance costs, of the basis of the given hourly patterns of the energy vector demand, of the operational modes and limits of the units, and of the purchase/sale prices of electricity at the electrical grid interface. The solutions are obtained through linear programming. The same paper [83] also contains an assessment of the possible convenience of performing alternative re-powering actions in the *long-term* time frame, carried out by comparing the alternatives on the basis of an energy efficiency indicator (the primary energy saving) and of an economic indicator (the net cash flow) for a specified set of scenarios. The paper [214] refers to a CHCP application in a hospital and adopts thermo-economic concepts for setting up a minimization of the weighted average exergy costs of electrical, thermal and cooling units. The optimization problem is solved by partitioning the complete system into subsystems and by using additional hypotheses for obtaining a solvable system with the same number of equations and unknowns.

Among the multi-objective formulations, [215] deals with minimizing simultaneously the annual production and purchase costs of the energy vectors, as well as the CO_2 emission costs. A planning model is formulated, in which the time frame is decomposed into thousands of hours, obtaining a separate

solution for each hour. The model is applied to different trigeneration plant configurations, generated on the basis of available components. Linear programming is adopted, by defining a specific Tri-Commodity Simplex algorithm that exploits the special structure and the convexity of the models used for the trigeneration case. The paper [98] develops an evolutionary multiple-objective algorithm to minimize simultaneously the annual total cost of power, heat and cooling generation as well as annual CO_2 emissions for a trigeneration system. In Ref. [93], a multi-objective optimization considering the minimization of the total annual costs (including operation and investment) and of the CO_2 emissions is set up with two nested cycles. The external cycle determines the equipment size by using evolutionary algorithms, and the internal cycle is dedicated to performance assessment (i.e., the evaluation of the optimal daily operation strategy for 12 daily load profiles representative of different types of daily operation during one year, structured as a linear programming model solved with the simplex method). The papers [124] and [125] refer to an integrated energy system providing gas, electricity, heat and cooling to a specified urban area. The optimization is set up as the search for optimal pricing of the various energy services, taking into account the emission constraints and the minimization of the annual costs for the consumers and for the multi-generation system, multi-generation. The pareto-optimal solution is found for the multi-objective problem.

Both *short-term* and *long-term* optimizations are addressed in [91] with reference to a trigeneration plant in a hospital site. Different optimizations are referred to the short-term time frame, by maximizing the *gross operational margin* (given by the difference between the management costs of the plant considered with respect to a conventional plant) and to the long-term time frame, determining the optimal size of the units by maximizing the *net present value*. The variables considered are the input and output powers of each unit, as well as the binary (on/off) states of all units, taking into account only full-load operation. Constant efficiency values are assumed for the equipment. The constraints are given by CHP size modularity, CHP performance, capacity limits and energy balances, and exclusive buy/sell option at the electrical grid interconnection.

Concerning *long-term* optimizations, the paper [92] deals with optimal design of a distributed multi-generation system for a specific urban district. The units are characterized by their performance functions to model partial load operation, obtained in polynomial forms from regression of manufacturers' data. The load patterns are assigned. The study involves energy efficiency, emissions and economic aspects, setting up a thermal-economic optimization model. The objective function is again the maximization of the net present value. The decision variables include type and number of gas turbines and gas engines, mass flow share of hot water and cold water at the gas turbine side, hot and cold water supply temperatures, and temperature of the pinch floor-cooling device. A mixed integer/nonlinear programming model is set up, and the solution is obtained by using genetic algorithms. A multi-scenario analysis is carried out for variable CO_2 and NO_x tax rates.

5. Concluding remarks

The development of DMG systems represents a close horizon for the future energy systems moving beyond the centralized and electricity-only generation paradigm.

This paper has outlined the main possible structures, characteristics, components, energy flows and interactions for DMG systems. In addition, several and various emerging approaches presented in the most recent scientific literature have been reviewed, that can be encompassed within the DMG paradigm.

Sustainability of the DMG solutions is guaranteed by a wide range of technical and economic benefits. In fact, DMG systems can provide the user with enhanced energy and environmental performance, higher quality of the energy services, and, in terms of economic operational optimization, the possibility of flexibly running the plant according to variable prices of gas, electricity, and of other energy-related commodities. In addition, DMG systems can bring an array of potential benefits to the community, including primary energy saving, optimal fossil and renewable energy sources exploitation, emission reduction of CO_2 and other hazardous pollutants, better electrical grid reliability and operation and thus decreased power system vulnerability.

The main ongoing issues concerning the DMG deployment refer to the integration of various DER, in case benefiting from regulatory incentives, the potential extended application of clusters of units (e.g., MTs) to residential/commercial energy districts, the possible exploitation of the micro-grid concept for managing dedicated areas as energy-integrated districts, the development of inverter technologies for network interface of DMG, embedding controlling capability for power quality improvement, and the development of adequate ICT for coordinating the DMG management. In this respect, various challenging aspects need to be solved, mainly due to the increased complexity of the multi-point connections to various energy networks and to the potential need of coordinated control actions for ensuring efficient or even optimal deployment of the resources.

The limitations to the DMG expansion in *urban* areas, where interconnected multi-generation systems could be best exploited, could be mainly due to regulatory constraints imposing limits to the local emission of specific pollutants worsening the air quality. However, the specific effects depend on the *marginal* pollution of the local generating units over the background level of pollutants existing in the environment (e.g., due to road traffic), on the presence of specific pollutants harmful for the human health, and on the specific characteristics of the *air pollutant dispersion* in the atmosphere. These aspects have to be evaluated case by case.

For an optimal planning of the DMG deployment on a broad basis, general evaluation instruments such as those based on LCA concepts would be needed to assess the DMG sustainability more thoroughly. Furthermore, application of the DMG concept would require establishing a dedicated regulatory framework enabling the energy system operators to proceed with the diffusion of upgraded high-efficiency low-emission technologies and of their applications.

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